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VIKING RADIO SCIENCE DATA ANALYSIS AND SYNTHESIS

Grant NAGW-411

Final Report

For the period 30 December 1982 through 31 March 1985

Principal Investigator

Irwin I. Shapiro

April 1985

Prepared for
National Aeronautics and Space Administration
Washington, DC 20546

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this grant is Dr. Henry C. Brinton, Code EL-4,
Solar System Exploration Division, NASA Headquarters, Washington, D. C. 20546.

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During the period covered by this grant, we made progress toward our primary objectives: (a) an investigation of the rotational motion of Mars and its geophysical ramifications, and (b) the study of solar-system dynamics and the laws of gravitation. We obtained a new bound on the rate of change of the constant of gravity G measured in atomic units

$$|\dot{G}/G| < 2 \times 10^{-11} \text{ per year}$$

and our studies continue to show that we can expect to reduce the uncertainty to 10^{-11} per year or less. This and other new results were presented at the May 1984 meeting of the AAS, Division of Dynamical Astronomy (DDA).

In the remainder of this report, we consider the recent technical progress which made possible our new results and which will be the basis of additional scientific results in the near future. This discussion is divided into three parts: A. Solar System Model and Data Set; B. Rotation of Mars; and C. Solar System Constants and Tests of Relativity. The last part includes the planetary masses and relativity results that were presented at the DDA Meeting.

A. Solar System Model and Data Set

The central element in our data analysis is the Planetary Ephemeris Program (PEP) which embodies our mathematical models of the solar system and observables. It functions as a weighted-least-squares fitting (and Kalman filtering) facility for observations related to the positions, velocities, rotations, etc. of solar-system bodies, natural and manmade. PEP contains approximately 10^5 lines of code, which is written mostly in Fortran with a small part in assembly language. It was originally

developed at the MIT Lincoln Laboratory where it is still in use. Over most of the past 17 years, the principal center of development has been the MIT Dept. of Earth and Planetary Sciences; at the beginning of CY1983, that center shifted to the Harvard-Smithsonian Center for Astrophysics. During the past few years, PEP has been systematically upgraded to take advantage of changes in computing and software-development techniques.

During CY83, the asteroid model in PEP was changed. We had been able to estimate the mass of a fictitious uniform ring and the masses of eight separate asteroids. (In an earlier modification, the latter had been increased from three.) More recently, the model was enhanced so that it is now also possible to estimate the densities of asteroids in up to five classes. This new model serves to include, at least approximately, the effects of up to 200 asteroids which are too small to consider individually but which may be important collectively. For each, the mass is the product of the density estimated for its class and an externally provided volume. Although this model has serious shortcomings, the dearth of applicable auxiliary data makes it a reasonable compromise. In our recent numerical experiments with the data, we have made use of the ability to estimate the larger number of individual asteroid masses and densities for the different asteroid classes.

About a year ago, we iterated the estimator a total of four times to obtain a stable, converged solution. During the first iteration, we added some new terms associated with the orientation of the planetary orbits. At the last iteration, we reintegrated all of the variational equations and included all of the new "cross partial" terms. At this time, we also increased the number of outer-planet orbital elements that could be estimated by including the required additional variational equations.

Finally, we recalculated the entire sensitivity matrix and recomputed the prefit residuals.

To investigate the results of the iterations, we performed a series of numerical experiments. We found our solutions to show more stability and the postfit residuals to show less systematic signature than before. Before the iteration, we had been unsuccessful in including in our solutions the Viking Lander delay data taken after 5 August 1980: When included, these data showed, and caused the other Lander delay data to show, a large systematic signature; their prefit residuals had a systematic signature with about a $5\mu\text{s}$ peak. (The same problem was encountered at JPL.) After the iteration, the postfit systematic signature was found to be reduced by roughly one-third. By increasing the number of estimated asteroid masses, we were able to remove about half of the remaining systematic signature. Finally, we included the outer-planet NPs (Earth-planet time-delay pseudo-data derived from the Doppler and ranging observations of spacecraft at encounter with the planet) and optical observations which permitted us to estimate an enlarged set of outer-planet orbital elements; the systematic signature became lost in the noise.

In the last few months of the grant period, we examined the relativistic terms included in our numerically integrated equations of motion. We decided to include some additional terms because it appeared that they could change the best of the observables by the order of their nominal uncertainty. After confirming that these terms were correctly added, we recalculated the prefit residuals and formed new normal equations. In a series of solutions of these normal equations, we found that none of the scientifically interesting parameters changed by as much as 50% of their formal uncertainty; most changes were closer to 10%. For

these scientifically interesting parameters, the realistic estimate of the uncertainty ranges from 2 to 10 times the formal estimate. Other parameters -- initial orbital elements of inner planets -- changed by as much as their formal uncertainty. These changes do not appear to have scientific consequences.

As part of our ongoing analysis, we found several months ago that our most recent ephemeris was rotated with respect to our most widely circulated ephemeris, PEP311. We evaluated several possible means of increasing the accuracy of the orientation of the ephemeris. After several quick calculations and some numerical tests, we concluded that the effort required to provide a fundamentally correct orientation to our ephemeris was very large and that the resulting benefits would be small: our principal scientific results depend on intra-solar-system measurements and are not sensitive to solar-system orientation. We therefore decided not to invest a major effort in this area. Instead, we applied an ad hoc rotation to our current ephemeris so that it and PEP311 would have the same average orientation during the year 1982.

We have maintained a low-level task intended to uncover and correct defects in PEP. We have been collaborating with our JPL colleagues on this task. In particular, we have been making comparisons between intermediate numerical products of their software and ours. We have found small discrepancies which have been traced to model errors in both sets of software. However, none of the corrections has thus far had a significant effect on the observables or our parameter estimates.

Our present working set of data is listed in Table 1. For discussion, we divide the Viking Lander delay data into two groups: those taken

through 5 August 1980, when the last dual-band calibration data were received from the Orbiter; and those taken between 6 August 1980 and November 1982, when the last Viking failed. Although the latter set lacks corrections for the effects of the solar plasma, the data that we use from this set are restricted to those taken at a time when the Sun-Earth-Mars angle was large and thus the plasma-induced errors in the measurement of the vacuum delay can be corrected approximately in the mean by use of a simple model. Thus, we have discarded the data taken near the time of the Mars superior conjunction of 2 April 1981; they require large plasma corrections that cannot be made usefully with a model. The errors assigned to the remaining data range from 2.5 to 5 times those that are assigned to data for which there are plasma density estimates from the Orbiter dual-band tracking.

A comparison of Table 1 with Table 2 of Reasenberg [1983], which is reproduced in the Appendix, shows four enlarged sets of data and one entirely new class of data. The extra plasma-corrected Lander delays are the result of the "discovery" in November 1983 of 150 lost data, an improved plasma correction method, and a re-evaluation of previously discarded data made fruitful in part by the improved solar-system model. The increased number of Lunar Laser NPs were obtained from our MIT colleagues (R. W. King, private communication). The two sets of radar data show a dramatic increase in the number of observations. This is the result of an implementation at Arecibo of a technique (Shapiro, *et al.*, 1972) by which simultaneous observations are made of a contiguous series of small regions along the planet's Doppler equator. Finally, the tracking station location data, which are entirely new in our work, are of two kinds. The first are VLBI interstation vectors. The second are from ground surveys of

the tracking station clusters.

The Viking Orbiter Normal Points (NPs) play a significant role in decreasing degeneracy in our solar-system analysis. The NPs were created by the (JPL) Viking Navigation Team using a small subset of the available data. As a result of unrelated work, we have techniques available with our software that would permit us to remake many of the NPs with more accuracy than the present set. We have investigated the possible scientific advantages of such a massive data-processing operation. Our covariance studies showed that there were no parameters of scientific interest that could be estimated significantly better by a substantial improvement in the NP set. We therefore will not seek funds for this work or suggest that it be performed elsewhere.

B. Rotation of Mars

In addition to precession and nutation [Reasenberg and King, 1979], our model of the rotation of Mars includes a secular rate of change of the period and both annual and semiannual variations in the phase of rotation [Williams, 1977, private communication; Philip, 1979; Reasenberg and King, 1979]. Our preliminary investigation with a 400-day set of Lander delay data provided a marginal detection of the semiannual terms [Reasenberg *et al.*, 1979] and showed that these could not be clearly distinguished from the annual terms with such a small span of data. A better result was provided by our initial study with an 800-day data set to which we applied the improved plasma estimates and data weights: The annual terms are found to be small and only moderately correlated in the estimator with the semiannual terms. The semiannual terms have an amplitude (expressed as an equatorial surface displacement) and a phase

(11.5 ± 5 m, $-2^\circ \pm 25^\circ$) consistent with the model of Davies et al. [1977] (10.5 m, -36°), but not so consistent with the model of Philip [1979] (9.6 m, -58°). The published measurements of atmospheric pressure [Hess et al., 1979] cover a time span insufficient for a meaningful comparison. The results of an analysis of a much longer span of Lander pressure measurements have been supplied to us by James Tillman who is preparing this material for publication [private communication, 1983, 1984] and distributed through the NSSDC. These data show that the general features of the annual and semiannual pressure fluctuations at the Landers repeat from year to year. The use of the Viking data to determine the amplitude and phase of the annual and semiannual terms in the rotation of Mars will provide one of the few independent constraints on global models of the circulation and condensation of the atmosphere of Mars. (See, for example, Shimazaki and Shimizu [1979] and references therein.)

We have modified our model of the rotation of Mars. In the old model, the seasonal irregularities were added to a spin rate that was constant in ephemeris time. In the new model, that spin rate is constant in Mars proper time, and therefore varies by about $\pm 10^{-9}$ in ephemeris time. The associated rotational phase shift is of the same order and phase as the predicted annual effect of the atmospheric condensation at the poles. The new relativistic correction is thus critical for the accurate determination of the amplitudes and phases of the proposed meteorological effects.

C. Solar System Constants and Tests of Relativity

At the June 1984 meeting of the AAS, Division of Dynamical Astronomy, Babcock [1984] and Chandler [1984] presented some of our recent results. Table 2 contains the values of planetary masses from Babcock's

presentation. In general, our results agree well with the latest values published in the Astronomical Almanac. Other results that they presented were improved estimates of the relativistic parameters; these are listed in Table 3. Finally, as a result of several small improvements, we have obtained a new estimate of the Earth-Moon mass ratio: $81.300589 \pm 1.5 \times 10^{-5}$. This is in very good agreement with the corresponding estimate given in the Astron. Almanac [1984]. See Table 2.

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Table 1. Combined Sets of Data

Source/Class ¹	Number of Data	Approximate Time Span of Observations	
		From	To
VIKING			
Lander delay (plasma corrected)	1041	July 1976	Aug. 1980
Lander delay (not plasma corrected)	239	Aug. 1980	Nov. 1982
Lander Doppler (plasma corrected)	11464	July 1976	Aug. 1980
Lander Doppler (not plasma corrected)	2539	Aug. 1980	Nov. 1982
Orbiter NP ²	4060	June 1976	Aug. 1977
LLR			
Observing session NP ³	3074	Sept. 1969	Aug. 1981
MARINER 9			
Orbiter NP ²	185	Nov. 1971	Oct. 1972
RADAR			
Mercury	4339	1969	1982
Venus	5464		
MERIDIAN CIRCLE ⁴			
Sun	1023	1970	1978
Moon	212		
Inner planets (M,V,M)	1518		
Outer planets (J,S,U,N)	1643		
OUTER PLANET NP ²	6	see note 5	
TRACKING STATION LOCATION		see text	

¹ All observables are time delays except for the Viking Lander Doppler, the meridian circle data, and the tracking station location data.

² The spacecraft Normal Point (NP) is a compressed datum: the equivalent two-way Earth-planet time delay that would have been measured between the centers of mass of the planets. All spacecraft NPs were obtained from the Jet Propulsion Lab where they were derived from the tracking data.

³ The Lunar Laser Ranging (LLR) Normal Point (NP) is a single estimate of the round trip propagation time between a tracking station and a single lunar retroreflector. The estimate is an average based on all photons received during an observing sequence. Under good conditions, there are as many as three sequences per day.

⁴ The data are a mixture of right ascension and declination measurements.

⁵ The epochs of the four Jupiter data are 12/4/73, 12/3/74, 3/5/79, and 7/10/79; those of Saturn are 11/13/80 and 8/26/81.

Table 2. Planet Mass Estimates¹

Planet ²	Mass Estimates		Differences Between Estimates	Standard Deviation (CfA)
	Analysis at CfA	Astron. Almanac (1984)		
Mercury	6,023,700	6,023,600	100	1000
Venus	408,523.1	408,523.5	0.4	1
Earth + Moon	328,900.554	328,900.550	0.004	0.003
Mars ³	3,098,750	3,098,710	40	60
Jupiter	1,047.3482	1,047.350	0.0018	0.002
Saturn	3,497.90	3,498	0.10	0.3
Uranus	22,830	22,960	130	300
Neptune	19,480	19,314	166	500
Earth/Moon ⁴	81.300565	81.300588	2.3×10^{-5}	1.5×10^{-5}

¹ All planet masses in inverse solar mass units except for the Earth/Moon ratio.

² The data are not sensitive to the mass of Pluto.

³ The CfA estimates of the mass of Mars does not use the spacecraft encounter data which dominate the estimate given in the Astronomical Almanac (1984, US Government Printing Office).

⁴ See last paragraph of text.

Table 3. Relativity Results Presented at the DDA Meeting, May 1984

Quantity	GR Nominal	Estimates ¹			Units
		#1	#2	#3	
J_2	N/A	-3±3			10 ⁻⁶
$\beta-1$	0	-0.025±0.05	-0.01±0.02		
$\gamma-1$	0	0. ±0.002	0. ±0.0015		
\dot{G}/G	N/A ²			0±2	10 ⁻¹¹ per year

¹ Each column represents a summary of results from a large number of solutions of the least-squares normal equations. The errors shown are realistic estimates of the standard deviation.

² Although general relativity does not address the possible time dependence of the relation between atomic and gravitational times, one normally assumes $\dot{G}/G = 0$ in classical physics.

The constancy of G and other gravitational experiments

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Traditionally, theories of gravitation have received their most demanding tests in the solar-system laboratory. Today, electronic observing technology makes possible solar-system tests of substantially increased accuracy. We consider how these technologies are being used to study gravitation with an emphasis on two questions:

(i) Dirac and others have investigated theories in which the constant of gravitation, G , appears to change with time. Recent analyses using the Viking data yield $|\dot{G}/G| < 3 \times 10^{-11}$ per year. With further analysis, the currently available ensemble of data should permit an estimate of \dot{G}/G with an uncertainty of 10^{-11} per year. At this level it will become possible to distinguish among competitive theories.

(ii) Shapiro's time-delay effect has provided the most stringent solar-system test of general relativity. The effect has been measured to be consistent with the predictions of general relativity with a fractional uncertainty of 0.1%. An improved analysis of an enhanced data set should soon permit an even more stringent test.

Technology now permits new kinds of tests to be performed. Among these are some that measure relativistic effects due to the square of the (solar) potential and others that detect the Earth's 'gravitomagnetic' field (the Lense-Thirring effect). These experiments, and the use of astrophysical systems are among the experimental challenges for the coming decades.

TABLE 2. COMBINED SETS OF DATA

source†	no. of data	approximate range of error assumed in estimator		unit
		min	max	
Viking				
Lander delay				
(plasma corrected)	798	20	60	ns
Lander delay				
(not plasma corrected)	263	50	300	ns
Orbiter n.p.‡	4060	100	900	ns
Lander Doppler	1075	20	40	mHz
I.L.R.				
Observing session n.p.§	2613	6	14	ns
Mariner 9				
Orbiter n.p.‡	185	0.1	10	μs
radar				
Mercury	642	1	15	μs
Venus	784	1	15	μs
meridian circle				
Sun	1023	≈ 2		"
Moon	212	≈ 0.5		"
inner planets (M, V, M)	1518	≈ 1		"
outer planets (J, S, U, N)	1643	≈ 1		"
outer planet n.p.	6	25	500	μs

† All observables are time delays except for the Viking Lander Doppler and meridian circle data.

‡ The orbiter normal point (n.p.) is a compressed datum: the equivalent Earth-Mars time delay measured between the centres of mass of the planets.

§ The lunar laser ranging (I.L.R.) normal point (n.p.) is a single estimate of the round trip propagation time between a tracking station and a single lunar retroreflector. The estimate is an average based on all photons received during an observing sequence.

|| The data are a mixture of right ascension and declination measurements.

¶ The outer planet normal point (n.p.) is a compressed datum from a spacecraft encounter with either Jupiter or Saturn. The n.p. is the equivalent Earth-planet time delay measured between the centres of mass of the planets.